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A New Tool to Forecast Fish Movement and Passage

A new technology — known as the Numerical Fish Surrogate™ — can aid the design of fish bypasses and guidance structures at hydro facilities by combining three types of modeling to forecast fish behavior and trajectories.

By R. Andrew Goodwin, John M. Nestler, James J. Anderson, and Larry J. Weber

All eight hydroelectric projects on the lower Snake and Columbia rivers in the Pacific Northwest feature bypass facilities that divert outmigrating salmon and steelhead away from the turbines and spillbays. Data from Snake River hydro projects indicate bypass system survival (95.3 to 99.4 percent) is generally comparable to that of spillbays (92.7 to 100 percent with flow deflectors and 98.4 to 100 percent without) and greater than that of turbines (86.5 to 93.4 percent).[1] Bypass systems are of keen interest because they can reduce both spill and passage-induced mortality. However, to date most bypass systems have achieved only limited and variable success.[2,3]

The key to good bypass design lies in understanding and forecasting a fish's response to the hydraulic (and sometimes water quality) conditions it encounters as it approaches a dam.[4] To this end, we developed a "plug-and-play" or "hypothesis testing" simulation tool, called the Numerical Fish Surrogate™ (NFS). The NFS integrates fish cognition and perception of hydraulic patterns; particle tracking; and computational fluid dynamics (CFD) modeling to accurately decode and forecast fish behavior and trajectories.

To match the movement and passage patterns of observed fish, the NFS uses small-scale individual movements of virtual fish responding to cues from a simulated flow field. The NFS then can be used to forecast the performance of alternative bypass and guidance strategies, as well as to describe the responses of fish to alternative project operations.

Developing the tool

The NFS uses the Eulerian-Lagrangian-agent method™ (ELAM), which combines: a Eulerian framework governing the physical, hydrodynamic, and water quality domains; a Lagrangian framework governing the sensory perception and movement trajectories of individual fish; and an agent framework governing the cognitive domain responsible for perception, behavior decisions, and acclimatization.[5]

The NFS runs on the highly resolved output of a CFD model, which simulates the flow field associated with a design or operational alternative. Then, with encoded algorithms based on quantitative knowledge of fish behavior with relation to flow fields, the NFS records the passage of individual virtual fish through the CFD model. If accurate, detailed, and coincident data are available on three-dimensional (3D) fish position and hydraulics, the NFS can be used to develop and test algorithms that relate fish movement to flow field attributes.

The NFS uses only hydrodynamic cues to elicit fish movement behavior based on the assumption that, near dams, hydraulics often dominate other stimuli. Successful model validation at four hydroelectric facilities supports this assumption.[5] However, many different cues (odor, light intensity, and social interactions among migrants) may influence fish behavior. Additional cues can be included in the NFS if their spatial distribution can be described.

How fish perceive hydraulic patterns

Fish perceive flow strength and direction, whole body acceleration, and spatial velocity gradients.[6,7,8,9] In addition, juvenile salmon are sensitive to pressure.[10] In the NFS, fish sensory perception is integrated with a basic concept of fluvial geomorphology that flow resistance creates flow pattern to produce a "fish traffic rule." We call this rule the strain-velocity-pressure (SVP) hypothesis. It requires three hydrodynamic cues — flow field distortion, velocity magnitude, and hydrostatic pressure.

We describe flow field distortion using a metric called "total hydraulic strain" that combines the fluid distortion mechanisms of linear deformation (whose tensor metric components are normal strain rates), rotation (whose components are angular velocities), and angular deformation (whose components are half of the true shearing strain rates). Total hydraulic strain is largely analogous to acceleration in steady-state flow, as it is simply the sum of the absolute values of

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all nine spatial velocity gradients. However, total hydraulic strain does not differentiate between acceleration and deceleration, which allows us to more simply separate sub-critical, steady flow resistance into two categories: friction and form resistance.

In a simple, straight, uniform channel, friction resistance produces a flow pattern in which average velocities are lowest nearest a friction source (such as the channel bottom), with zero velocity occurring at the interface between the water and the friction source. The lowest total hydraulic strain occurs furthest from sources of friction resistance, and the highest occurs nearest the sources.

Form resistance occurs when objects, such as rocks, project into the flow field. As with friction resistance, total hydraulic strain associated with form resistance increases toward the source. By contrast, water velocity increases toward the source of form resistance because of local reduction in conveyance area and increased travel distance of water flowing around an obstruction. For example, a fish approaching a rock outcrop from upstream senses increased total hydraulic strain and water velocity until it encounters solid boundary effects very close to the obstruction.

By integrating information between the total hydraulic strain and velocity fields, fish can differentiate structures associated with friction or form resistance and create a hydrodynamic "image" of their surroundings. This image is of sufficient resolution to guide swim path selection. As they evolved in free-flowing rivers, fish learned that hydraulic patterns in their near-field environment provide information on the environment beyond their sensory range. The SVP hypothesis approximates how migrants select swim paths that minimize migration time, bioenergetic cost, and exposure to predators and objects.

We note that, to maintain neutral buoyancy during depth changes, fish with swim bladders can alter the amount of gas in the bladder. The process is energetically cheap but slow.[11] Therefore, the SVP hypothesis characterizes the fish's depth changes in terms of its response to friction and form resistance, limited by its ability to adjust swim bladder volume, not its vertical swimming velocity.

Modeling fish response to hydrodynamic cues

Within the NFS, we relate fish cognition and movement to hydrodynamic cues using agent-based modeling concepts. Agents — independent "operators" that can move and react with others in a virtual environment — are a mathematical way of representing animal perception.[12] The NFS considers hydrodynamic cues to be agents that interact with the fish. Executing the SVP hypothesis as a behavioral rule requires four agents: absence of other agents (A_0), friction resistance (A_1), form resistance (A_2), and pressure gradient (A_3). Fish perceive agents as events by their hydraulic signatures. Fish perceive friction resistance agent A_1 when total hydraulic strain exceeds an intensity threshold of k_1, and fish perceive form resistance agent A_2 when total hydraulic strain exceeds a threshold of k_2, where k_2 is much greater than k_1. Fish perceive pressure gradient agent A_3 when the change in hydrostatic pressure exceeds a threshold of k_3.

Animals do not perceive the intensity of a stimulus according to the metrics we use to measure or model them. For example, the volume control dial on an audio amplifier might be labeled in decibels (perceived intensity) instead of voltage amplification (measured intensity). The decibel scale is often used to measure sound intensity that, according to the Weber-Fechner Law, is a good fit to loudness perception. We assume fish perceive the intensity of total hydraulic strain (flow field distortion) at a given time t, following an analogy to the decibel scale. That is, the fish's perception of flow field distortion, I(t), is not linear with the physically measured or modeled intensity of total hydraulic strain, S(t). Instead, fish perceive flow field distortion as varying linearly with the log transform of total hydraulic strain:

Equation 1:

$$I(t) = \log_{10} [S(t)/S_0]$$

where:

— I(t) is the total hydraulic strain

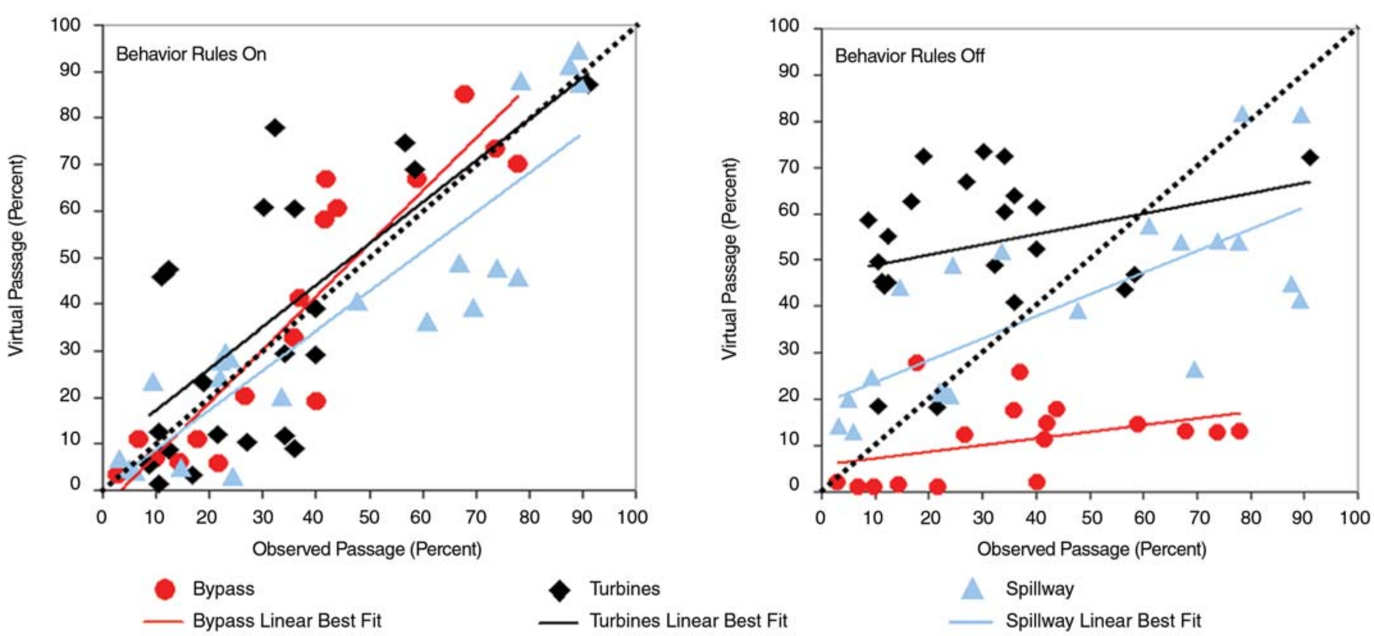

Figure 1: Comparison of observed (measured) and virtual (Numerical Fish Surrogate or NFS) fish passage proportions show the NFS successfully forecasts passage. With the behavior rules turned on (at left), NFS forecasts largely capture the trends in observed passage. With the behavior rules turned off (at right), the virtual fish do not provide appreciable information on passage trends at the projects.

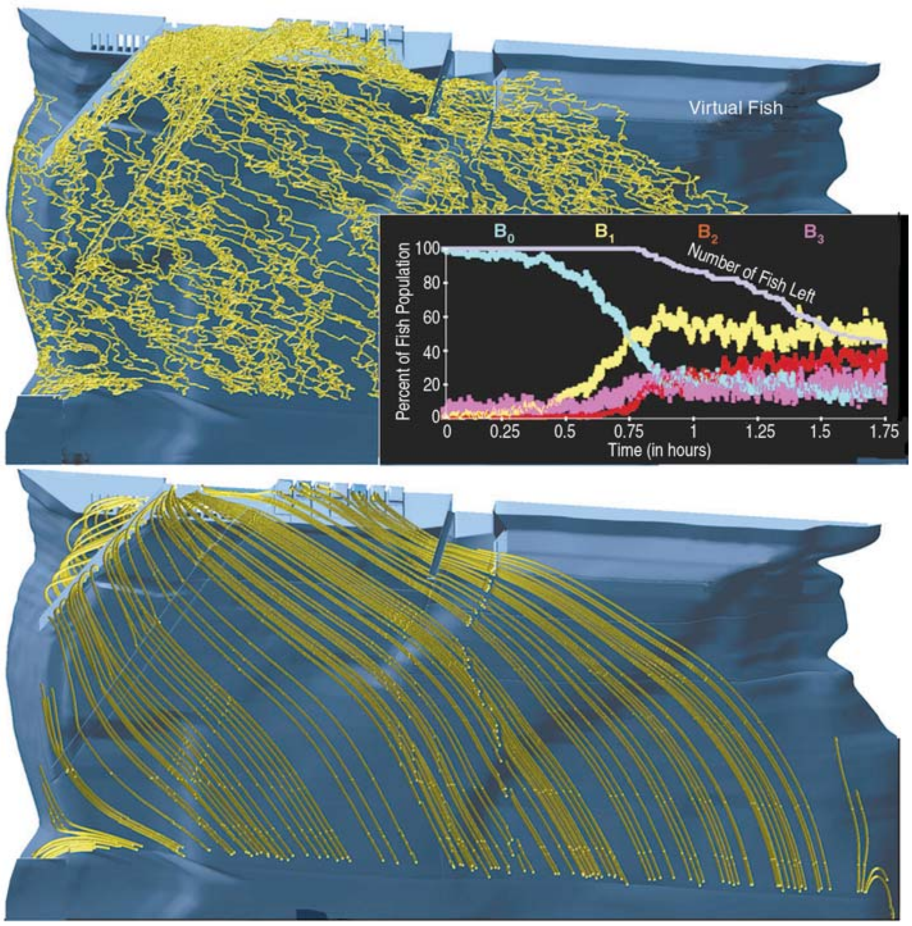

Figure 2: Researchers tracked virtual fish movement upstream of the 810-MW Lower Granite Dam with (top) and without (bottom) consideration of fish behavior. In the top view, fish behavior causes changes in movement. Upstream from the dam, behavior B_0 predominates. As the fish move closer, their behavior, and consequently their movement, changes (to B_1, B_2, and B_3). This resembles observed fish movement at Lower Granite. In contrast, when behavior is not considered, virtual fish simply follow the water flow (bottom).

(flow field distortion) as perceived by the fish;

— $S(t)$ is the total hydraulic strain as physically measured or modeled and equals the sum of the absolute values of all nine spatial velocity gradients; and

— S_0 is a reference value to quantify intensity relative to an arbitrary datum.

The Weber-Fechner Law indicates that to detect a change in stimulus intensity, $I(t)$, it must exceed the background intensity to which the animal is acclimated, $I_a(t)$, by a "just noticeable difference." Thus, the fish's exposure history plays an important role in determining behavior response. When a stimulus intensity exceeds the background level by the "just noticeable difference," a detection event results and the motivation to respond to agent A_i increases by an increment. The algorithm for this process is:

Equation 2:

$$I(t)/I_a(t) > k_i$$

where:

— $I(t)$ is the total hydraulic strain as perceived by the fish;

— $I_a(t)$ is the perceived background intensity of total hydraulic strain to which the fish is acclimated; and

— k_i is the threshold level, either k_1 associated with the friction resistance agent A_1 or k_2 associated with the form resistance agent A_2.

Equation 2 implies that a larger change in total hydraulic strain is needed to detect agent A_1 or A_2 at higher background levels than at lower levels.

We characterize the acclimated background level using an exponentially weighted moving average (EWMA) of the fish's exposure history:

Equation 3:

$$I_a(t) = (1-m_{strain}) \times I(t)+m_{strain} \times I_a(t-1)$$

where:

— $I_a(t)$ is the perceived background intensity of total hydraulic strain to which the fish is acclimated;

— m_{strain} is an adaptation coefficient with a value between 0 and 1 that scales how quickly the fish adapts to new total hydraulic strain conditions;

— $I(t)$ is the total hydraulic strain as perceived by the fish; and

— t is time.

EWMAs have a long history in psychological and signal processing literatures.[13,14]

Fish may change depth in response to the friction resistance, form resistance, or pressure gradient agent. In contrast to the logarithmic scale characterizing total hydraulic strain perception, we assume the fish's perception of pressure varies with the linear difference between its present depth and acclimated depth. The motivation to change depth in response to pressure gradient agent A_3 increases when the difference between the perceived and acclimated depths exceeds a threshold value of k_3. Acclimatization to new depths (pressures) is calculated with an EWMA:

Equation 4:

$$d_a(t) = (1-m_{depth}) \times d(t)+m_{depth} \times d_a(t-1)$$
$$m_{depth} = C_d \times m_{depth} \text{ if } d(t) < d_a(t)$$
$$m_{depth} = m_{depth} \text{ if } d(t) \geqslant d_a(t)$$

where:

— $d_a(t)$ is the depth to which the fish is acclimated;

— m_{depth} is an adaptation coefficient between 0 and 1 that scales how fast or slow the fish adapts to new depths;

— $d(t)$ is depth; and

— C_d is a coefficient between 0 and 1 acknowledging that filling the swim bladder to descend is slower than emptying gases to ascend.

The detection of an agent is treated as a Boolean event, $e_i(t)$.[15] For example, $e_i(t)=0$ if the agent stimulus does not exceed threshold level k_i in a time increment and 1 if it does. This is expressed as:

Equation 5:

$$e_i(t)=0 \text{ if } I(t)/I_a(t) < k_i$$
$$e_i(t)=1 \text{ if } I(t)/I_a(t) \geqslant k_i$$

where:

— $e_i(t)$ is a Boolean event measure;

— $I(t)$ is the total hydraulic strain as perceived by the fish;

— $I_a(t)$ is the perceived background intensity of total hydraulic strain to which the fish is acclimated; and

— k_i is the threshold level, either k_1 associated with the friction resistance agent A_1 or k_2 associated with the form resistance agent A_2.

Boolean events allow threshold intensities of hydrodynamic cues to trigger fish movement through "motivation" and also mathematically describe "response latency" (the time interval between a stimulus and the response).[16,17]

However, relating agent detections to fish responses is not straightforward because fish simultaneously acquire many information streams, each of which may produce a specific behavior. We use a game theoretic framework to link agent detection to fish response.[15] In this framework, a fish estimates the probability of obtaining the intrinsic utility of a behavior using information streams acquired by its sensory system. All behaviors have bioenergetic costs, so expected utility from behavior is:

Equation 6:

$$U_i(t) = P_i(t) \times u_i - C_i(t)$$

where:

— $U_i(t)$ is the expected utility or level of motivation for responding to agent A_i with behavior B_i;

— $P_i(t)$ is the probability of obtaining the utility or benefit associated with successful implementation of behavior B_i in response to agent A_i;

— u_i is the intrinsic utility or value of the benefit associated with successful implementation of behavior B_i relative to the benefit from alternative behaviors; and

— $C_i(t)$ is the bioenergetic cost of behavior B_i, regardless of its success.

In this framework, a fish updates probabilities for each behavior at each time step t and selects the behavior with the greatest motivation (expected utility U_i). The probability estimate at time t depends on the estimate at t-1. New information available between t-1 and t is summarized using an EWMA, so the probability of obtaining intrinsic utility u_i is:

Equation 7:

$$P_i(t) = (1 - m_i) \times e_i(t) + m_i \times P_i(t-1)$$

where:

— $P_i(t)$ is the probability of obtaining the utility or benefit associated with successful implementation of behavior B_i in response to agent A_i;

— m_i is a memory coefficient with a value between 0 and 1 that determines how the fish weighs current information in $e_i(t)$ against past information regarding agent A_i embodied in $P_i(t-1)$; and

— $e_i(t)$ is the Boolean event measure indicating the presence or absence of agent A_i.

Maintaining information across time using an EWMA produces persistence in behaviors where fish behavior during time increment t to t+1 depends on acclimatization to past conditions. This is an important feature in modeling animal movement.[18,19]

The four agents (A_0, A_1, A_2, and A_3) are associated with four behaviors: swimming with the flow vector (B_0), swimming toward increasing water velocity to minimize total hydraulic strain (B_1), swimming toward decreasing water velocity or against the flow vector to minimize total hydraulic strain (B_2), and swimming toward acclimated pressure (depth) (B_3). Swimming speed is bounded between burst speed (about ten body lengths per second) and nominal cruising speed (about two body lengths per second).[20] In each time increment, fish orientation and speed are set by the threshold triggered behavior B_i plus a random component.

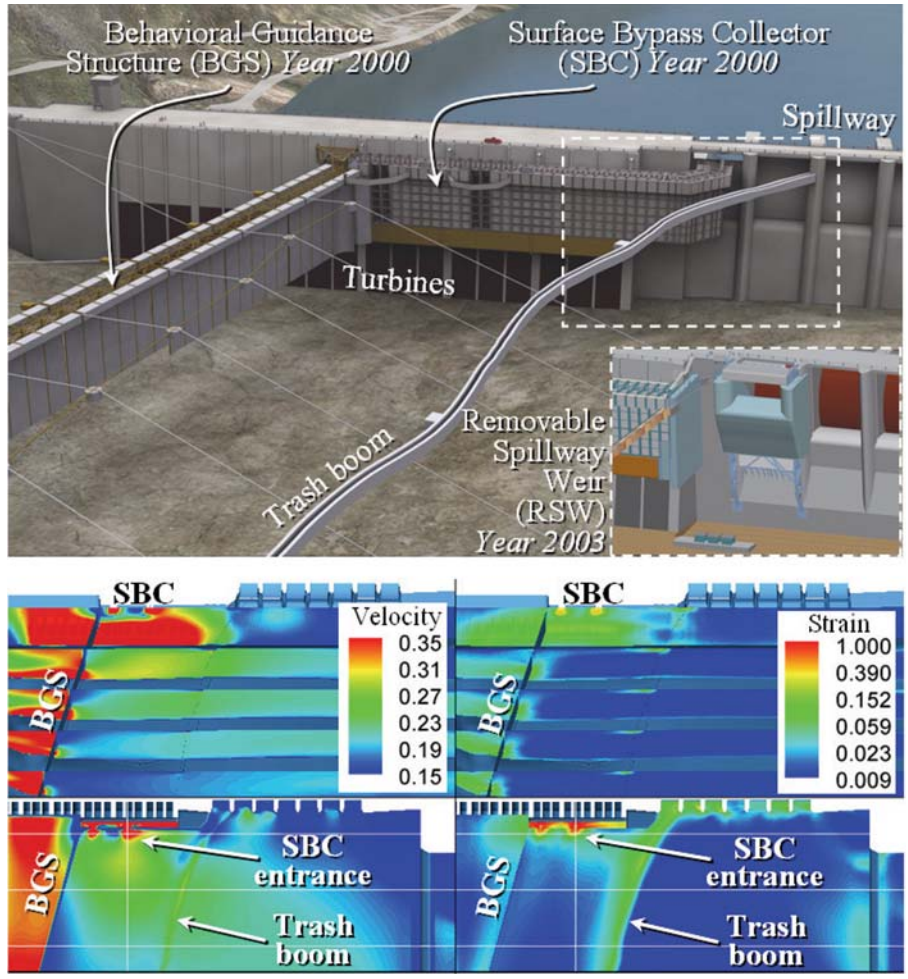

Figure 3: Fish guidance systems at 810-MW Lower Granite Dam include a behavioral guidance structure (BGS) that guides fish to the surface bypass collector (SBC) and occludes them from the three turbine intakes nearest the shore. Patterns of velocity and total hydraulic strain in 2000 are illustrated using cross-sections parallel to the dam face at 50-meter intervals (middle) and a horizontal plan view near the water surface (bottom).

Incorporating data into the tool

Three sets of data must be integrated to configure the NFS model for new facilities and species:

1) Behavior: highly resolved time- and space-accurate 3D positions of individual fish movement in a relatively constant hydraulic field;

2) Passage: accurate exit-specific passage information of target fish groups; and

3) CFD model: detailed model simulations that accurately describe flow field patterns associated with behavior and passage data.

Behavior data is required for development of a movement hypothesis, passage data is required for model calibration and validation, and CFD model data is required for calibration, validation, and forecasting. Furthermore, CFD model data must be correctly synchronized with behavior and passage data to ensure prototype biological information is cor-

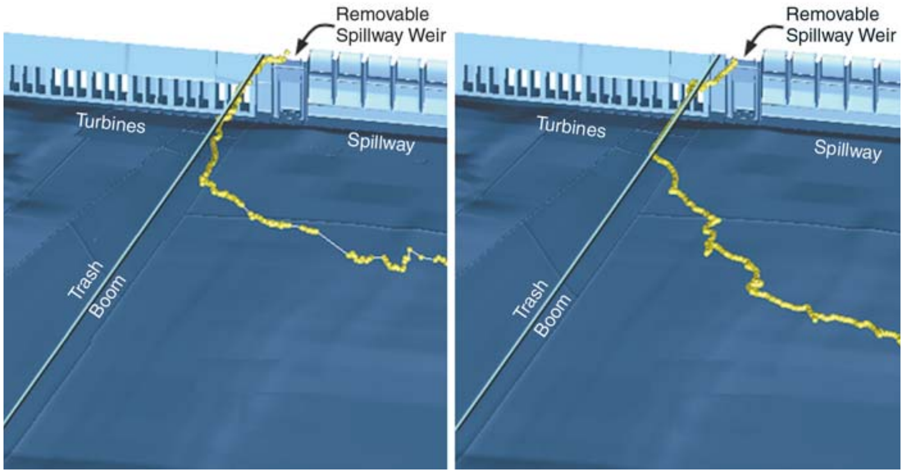

Figure 4: Real, acoustically tagged fish (at left) and virtual fish (at right) have similar responses to the trash boom at the 810-MW Lower Granite Dam. When both the real and virtual fish pass near the boom, they divert from following the flow and instead follow the boom toward the removable spillway weir.

rectly matched to project operation.

Model application

NFS algorithms and the SVP hypothesis were developed and calibrated using acoustic-tag telemetry and passage data from a single structural/operational configuration at 810-MW Lower Granite Dam. Then, the NFS was validated against 19 structural/operational configurations — 12 at Lower Granite, two at 603-MW Ice Harbor, and five at 1,038-MW Wanapum Dam.[5]

We evaluate NFS performance using five metrics:

1) Ability to capture trends in measured passage at multiple hydro projects. Linear regression of measured vs. forecasted passage shows the NFS successfully hindcasts passage for 23 configurations, which includes the 20 mentioned above and three new configurations at 1,812.8-MW The Dalles Dam. (See Figure 1.) Mean slopes/r-squares for the 23 configurations are 0.90/0.82 for the bypass, 0.78/0.80 for the spillway, and 0.67/0.43 for the turbine passage routes.[21] Mean slopes/r-squares of 1.0 are optimum, while r-square values above 0.65 are considered useful for decision-making.[22] For comparison, mean slope/r-square values from the original calibration/validation of 20 configurations were 0.74/0.78, 0.77/0.89, and 0.82/ 0.65, respectively.[5]

2) Ability to forecast passage better than passive particles (dye in a physical model). (See Figure 2.) Colored dye often is used in combination with physical models during project planning to gauge plausible fish movement and passage. Passive particle tracks in a CFD model are analogous to dye streaks in a physical model. Within the NFS, virtual fish become passive particles when the behavior rules are "turned off."All NFS forecasts with the behavior rules turned off result in passage forecasts substantially less than the 0.65 r-square threshold. In comparison, almost all "rules on" forecasts produce r-squares above this threshold. (See Figure 1.)

3) Ability to correctly rank alternatives by passage performance. The NFS forecasts generally match measured rankings of configurations as top-, moderate-, and low-performing, using the metric of passage per unit of CFD modeled flow for the bypass, spillway, and turbines.[5] By comparison, rankings based on passive particles are poor.

4) Ability to explain performance of individual bypass and guidance structures. The NFS explains the reasons behind performance of several significant hydraulic structures, such as The Dalles Dam sluice and occlusion plates; the Lower Granite removable spillway weir (RSW), behavioral guidance structure (BGS), surface bypass collector (SBC), and trash boom; and the Wanapum top spill bulkhead and sluice.[21]

5) Ability of NFS to replicate predominant 3D movement patterns of individually tagged fish. Movement patterns of individual virtual fish generally match the predominant patterns of individual acoustically tagged fish encountering similar hydraulic features. This metric is critical because total passage is the sum of individual behaviors and cannot be accurately forecast unless individual behavior is captured.

Both the trash boom and SBC at Lower Granite exhibit unique hydraulics (velocity and total hydraulic strain). (See Figure 3.) These hydraulics are either friction or form resistance.

Examples illustrate the match of NFS virtual and real fish behavior at the trash boom and SBC at Lower Granite. In the first example, the NFS duplicates the trash boom-following behavior of real fish. (See Figure 4.) This is depicted in a 100-second sequence beginning at 2,076 seconds. (See Figure 5.) The fish first detects the strain created by the trash boom at 2,120 seconds, when the perceived change (i.e., the just noticeable difference) in strain exceeds threshold k_1, which is the level the fish associates with friction resistance (A_1). During the time the threshold k_1 is exceeded, the resulting events $e_1(t)$ identifying agent A_1 increase the expected utility U_1 (yellow utility line in Figure 5), which is the motivation to respond to agent A_1 with behavior B_1. After eight seconds, utility U_1 exceeds U_0 and the fish switches from swimming with the flow (B_0) to swimming toward increasing water velocity (B_1) to reduce strain exposure. This delay between agent identification and response is the response latency.[17] The net result is that the fish breaks off from the flow and follows the trash boom toward the dam. Because the boom's effect on the flow field dissipates with depth, neither deeper-swimming virtual nor real fish respond to the boom.[5]

In the second example, the NFS duplicates fish milling between the SBC and trash boom, depicted at between 2,920 and 3,200 seconds. (See Figure 5.) In the high-energy SBC environment, the virtual fish's perceived change in strain exceeds k_2 at 2,928 seconds. This signals the presence of agent A_2, and the resulting events $e_2(t)$ increase utility U_2. After a 50-second latency, U_2 exceeds U_1 and the virtual fish switches to swimming upstream (B_2) to reduce strain exposure. Even though strain diminishes as the fish moves away from the SBC, the fish continues swimming upstream because of response latency (i.e., although decreasing, the utility U_2 of behavior B_2 still exceeds the utility U_1 of behavior B_1). At 3,182 seconds, the fish swims past the trash boom, the perceived change in strain drops precipitously, events $e_1(t)$ and $e_2(t)$ stop, and utilities U_1 and U_2 decline. Eventually, the utility drops below U_0 and the fish resumes swimming with the flow (B_0).

This cycle between the three behaviors produces milling between the trash boom and SBC. However, because the acclimated strain, $I_a(t)$, increases with each visit to the SBC, the milling is eventually disrupted when the perceived change in strain at the SBC entrance does not exceed k_2. At this time, the fish either swims with the flow (B_0) or into increasing water velocity (B_1). With either action, the fish enters the SBC.[5]

Model assessment

Fish guidance and bypass structure designs are based on hydraulic information from physical and computational models, patterns derived from statistical analyses, and the experience and judgment of engineers and biologists. The NFS is designed to supplement these approaches by adding unique capabilities to guidance and bypass efficiency forecasting.[23]

First, the NFS uses velocity and distortion field information (approximated by total hydraulic strain) to characterize the hydrodynamic cues fish use. Second, the NFS simulates how fish perceive and respond to the hydraulic regime by using response latencies and adaptive behaviors observed in laboratories. The SVP hypothesis indicates that regional bypass design criteria based on average hydraulic conditions and velocities will be ineffective. Fish respond and adapt to hydraulic gradients, not absolute velocities. Thus, systems designed on average conditions cannot address fish experience and resulting adaptation.

Data quality and project complexity varied substantially across the 23 scenarios studied and likely influenced accuracy of individual project and combined forecasts. Future NFS use will be most efficient when: calibration/validation data exhibit a high degree of synchrony between project operation, CFD model scenario, and fish passage information; and the CFD models are calibrated and benchmarked to ensure the meshes do not adversely affect simulated hydraulic gradients.

Our analysis reveals that NFS accuracy is highest for forecasting spillway passage, intermediate for bypass passage, and lowest for turbine passage. This order likely reflects variability in outlet flows during field data collection: spillway operations were held constant during studies, but turbine operation varied in response to electrical demand and maintenance requirements. Bypass system performance is affected by turbine operations because these systems often are located near the powerhouse.

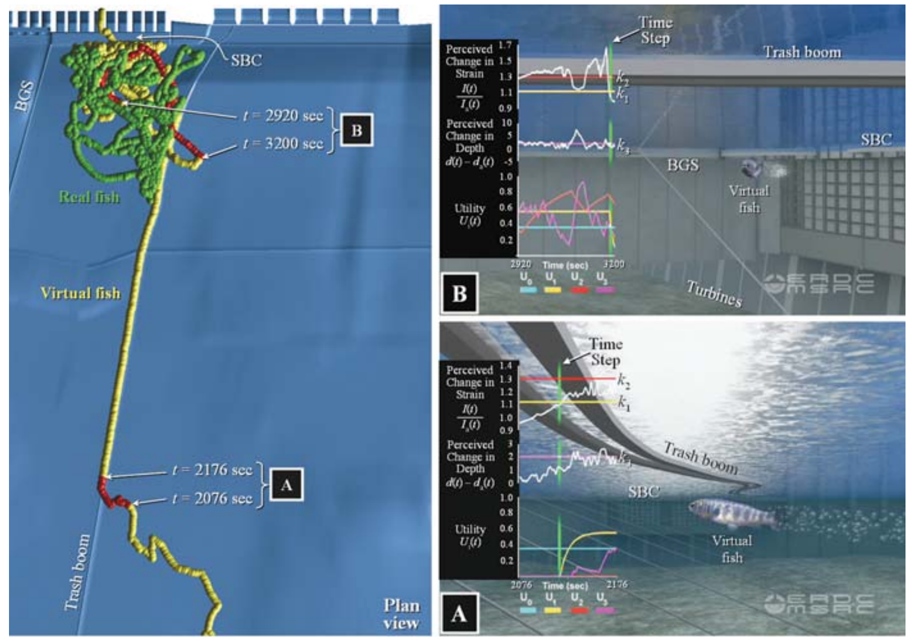

Figure 5: Tracks of virtual fish (yellow) resemble the trash boom-following and milling behavior of real fish (green). Second-by-second changes in the perceived change in strain and depth drive the utility (i.e., motivation) for four behaviors, which act in concert to explain why fish follow the trash boom (A) and mill in front of the bypass collector (B) before passing downstream.

A major component of NFS error likely results from the inability of the steady-state CFD model to capture the time-varying turbine operations under which fish passage data were collected. For example, ten of the 23 configurations were associated with lumped passage data (passage for individual turbines or spillbays was not separated). For the other 13 configurations, passage estimates were provided for individual turbines and spillbays. For 12 of these 13 configurations, fish passage was measured through turbines or spillbays that are closed in the CFD model (mean 4.2 percent; range 0.03 to 11.31 percent). We do not know if turbine operation was held constant during collection of the lumped passage estimates.

Besides synchronization error, well-executed fixed-location hydroacoustic monitoring studies have errors of about ±5 percent of actual passage. Increased synchronization during passage monitoring and improved accuracy of fixed-location hydroacoustics will provide higher-resolution data that will increase the accuracy of the NFS.

Species-specific NFS versions are possible, but data are insufficient to rigorously develop, calibrate, and validate a model. Also, development of a species-specific NFS likely will require increased resolution of CFD model meshes; an evaluation of the steady-state assumption used in the present formulation of the NFS; and increased efforts to synchronize project operation, CFD modeling, and fish positional and passage data collection.

The distortion field is easier to affect than bulk flow patterns. Our research indicates that relatively small structures — such as trash booms — can substantially affect fish behavior by affecting the distortion field. This finding can help identify innovative new cost-effective guidance and bypass technologies that take advantage of flow field distortion to adjust the fish distribution.

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